Assessment of suitable configurations for combined Solar Power and Desalination plants

Julián Blanco, Patricia Palenzuela, Diego Alarcón, Guillermo Zaragoza, Elena Guillén, Mercedes Ibarra

CIEMAT-Plataforma Solar de Almeria. Environmental Applications of Solar Energy Unit
Ctra. de Senés s/n, 04200 Tabernas, Almeria, Spain

Abstract

The paper describe and discuss different suitable configurations for the effective integration of desalination technologies into concentrating solar power plants using low grade steam from the turbine to drive conventional thermal desalination units. Used methodology analyzes the combined efficiency in the power and water production considering the following options:
CSP co-generation plants combined with thermal seawater desalination (MED). Their electricity can be used for additional Reverse Osmosis desalination (RO), for domestic electricity consumption or for export. The main disadvantage of this option is the need to be located near seacoasts, which are usually heavily used for other human activities. In addition, direct normal solar irradiation is normally lower in coastal locations, limiting this type of plant to regions with appropriate site conditions and available land area.
CSP Plants used exclusively for power generation can be located anywhere on the grid. Their electricity can then be transmitted to the RO-desalination plant site. This type of plant can be placed where good irradiation coincides with good infrastructure conditions.
When costs are analyzed, comparing the two more efficient configurations (PT-CSP/RO and PT-CSP/LT-MED), considering 58ºC/0.18 bar of exhaust turbine steam conditions and 5.5 kWh/m^3 of Reverse Osmosis power requirements, the results are very similar.

Keywords

Power and water polygeneration, concentrating solar power and desalination

Introduction

The typical geographical coincidence of water shortage and other water problems and high solar radiation is widely recognized [1], so the use of solar energy to simultaneously address water and power production is one of their most sustainable solutions. Therefore, integration of water desalination technologies in concentrating solar power plants is a relevant area of Concentrating Solar Power (CSP) research, and if successful, will certainly accelerate the large-scale implementation of solar energy, especially in regions where fresh water is scarce.
One of these regions is Middle East and North Africa (MENA), where the combination of significant population growth, expected to increase from 500 million people in 2000 to about 700 million in 2025 [2], strong energy demand, expected to increase from 1300 TWh/year in 2000 to about 2500 TWh/year in 2025 [2], and also high water demand, expected to increase from 300 billion m^3/year in 2000 to about 450 billion m^3/year in 2025 [2], anticipate

Corresponding author: Dr. Julian Blanco Galvez, email: julian.blanco@psa.es, phone: (+34) 950387939, fax: (+34) 950365015

problematic feasible scenarios in the coming years/decades due to the very limited renewable water sources and the current nearly complete dependence of fossil fuels [3]. Considering the previous context in the specific case of MENA countries, it is difficult to imagine any adequate solution without a significant contribution of renewable energies, being solar energy the first obvious candidate to be introduced due to its vey high potential in the region. Also, among different solar energy technologies, concentrating solar power has the highest potential [4], being this the reason why large solar development plans and projects, such as the Desertec Initiative [5] and Mediterranean Solar Plan [6], are currently underway in the MENA region. Specific CSP projects are already been developed, such as the ones in countries like Morocco (Ain Beni Mathar), Algeria (Hassi-R'mel) or Egypt (Kuraymat), or are under development (Abu Dhabi) also existing plans for large development of solar energy at defined countries, such as Algeria and Saudi Arabia. Technology to make possible these developments is ready being today the main problem the financial one [7].

If today's solar thermal technology to power production is available and market ready, the next logical step to make CSP technology even more attractive at regions such as MENA would be the integration of Desalination (CSP+D) into solar power plants. Combined CSP+D facilities could be a very good solution because an adequate integration could provide a number of attractive benefits to the concept, such as:

- Technological existing synergies can potentially reduce the cost of combined power and water production over the production of each of them alone.
- Financing could also benefit, as the cost of water and power can be better adapted to the specific local conditions of the facility.
- Politically, it is a win-win situation, as it is much easier to solve potential (administrative) problems if there are clear gains to both facility promoter and host.

However, in addition to all the potential benefits of combined power and water production, desalination integration into concentrating solar power plants is not a straightforward issue yet, as there are several unsolved technological issues, which still need specific research, development and demonstration initiatives to define the best concepts and systems [8].

One of these issues is the definition of the best configuration when thermal desalination technologies coupled with a parabolic-trough (PT) solar power facility (using low grade steam from the turbine to feed a MED unit) compared with the reverse osmosis option (electricity from the power facility is used at RO plant either in the same or in different location).

Studies on different basic integrated power and desalination plants configurations have been published, such as the description of the operation of low-temperature multi-effect distillation (LT-MED) desalination plants using low grade steam from different power plants [9]. Other studies address the energy cost analysis to produce water from an integrated power plant into LT-MED and thermal vapor compression MED (TVC-MED) units [10], evaluate the benefits of integrating RO units with existing power/desalination plants in the Middle East [11], or perform thermo-economic analysis of different configurations for the combination of a reverse osmosis subsystem to produce drinkable water and a steam power plant to generate electricity [12]. Considering the specific case of CSP+D plants, some studies shows the potential of CSP plants coupled with desalination systems (RO and MED) for MENA region [13] and techno-economically analyze the combination of parabolic trough power plants for electricity production with MED and ultrafiltration/RO plants [14], [15].

This paper address the technical analysis, from the thermodynamics efficiency point of view, of different configurations integrating solar power and desalination and the economic assessment of the two options considered as more promissory.

Methodology

Two types of LT-MED plants have been considered: using the exhausted steam from the CSP plant as the source of the heat, and a novel system consisting of low temperature multi-effect distillation plant powered by the steam produced from a thermal vapor compressor (TVC). In this case, unlike typical TVC-MED process, the vapor to be used in the steam ejector comes from the exhausted steam of the CSP plant instead of an intermediate effect of the desalination unit. This new concept has a strong potential since is useful for the coupling of any thermal desalination process to a CSP plant. Within this concept (LT-MED-TVC), different schemes have been studied: a system that uses the high exergy steam at the high pressure turbine outlet as motive steam in the TVC, and others that use steam extracted at different pressures from the low pressure turbine as the motive steam in the ejector. The results indicate that the integration of a LT-MED plant into a PT-CSP plant is the most efficient thermodynamically of all configurations proposed, besides no power cooling is required and therefore any condenser would be necessary.

Figures 1-4 show the systems under consideration. They each consist of a parabolic trough concentrating solar power (PT-CSP) plant based on Reheat Rankine cycle with water as the working fluid and a desalination system operating under steady state conditions. The desalination technologies considered are: LT-MED (Fig. 1), LT-MED-TVC (Figs. 2-3) and RO (Fig. 4). On one hand, the integration of the LT-MED unit into a CSP plant allows to replace the conventional cooling unit of the steam cycle compared to the case of a conventional CSP plant connected to a RO system. On the other hand, the integration of a LT-MED-TVC unit has a big interest since it is useful for the coupling of any thermal desalination process to a power plant and not only for a MED process. In this case, unlike the conventional TVC-MED process, the vapor to be used in the ejector comes from the exhausted steam from the LP turbine instead of an effect of the MED unit. In this context, in order to optimize the heat extraction of the LT-MED-TVC integration, steam extractions at different pressures are made in the low pressure turbine.

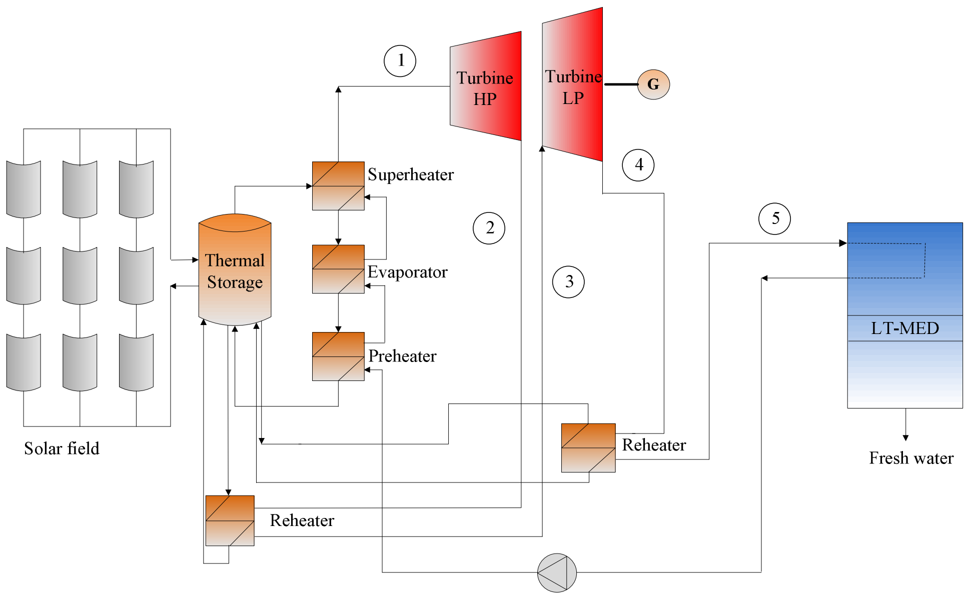

Fig 1. Diagram of the LT-MED unit integration into a PT-CSP plant

The CSP plant consists of parabolic-trough (LS3 type) collectors aligned on a North-South orientation and a thermal storage tank to provide additional operation when solar radiation is not available. Collectors can track the sun from east to west during the day to ensure it is continuously focused on the linear receiver, being PT-CSP technology the same in all the configurations. As it can be observed in Figs. 1-4, steam at 1 is generated from the thermal energy collected by the solar field. It is subsequently sent to a high pressure turbine where, after suffering an expansion process is extracted at 2 in order to reheat it. The reheated steam is left to its expansion through a LP turbine up to 4 in the first case and up to 6 in the rest, obtaining the required power. The desalination plant considered in the first configuration (PT-

CSP + LT-MED, Fig. 1) is fed at 5 by the low temperature steam from the turbine outlet after being reheated to obtain saturated steam without increasing the temperature. In the second case (PT-CSP + LT-MED-TVC, Fig. 2), part of the steam at 2 is used as motive steam in a steam ejector after passing trough a reheater to achieve saturation conditions. Moreover, one part of the exhausted steam from the turbine at 6 is used as entrained vapor in the ejector. Then, the resulting compressed vapor from the ejector is injected into the first effect of the distillation unit at 5, driving the thermal desalination process.

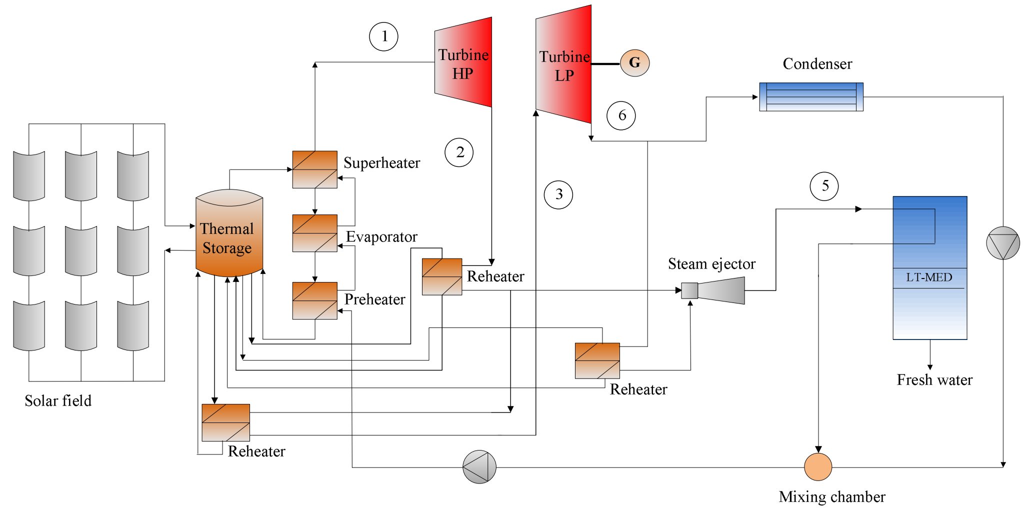

Fig 2. Diagram of the LT-MED-TVC unit integration into a PT-CSP plant

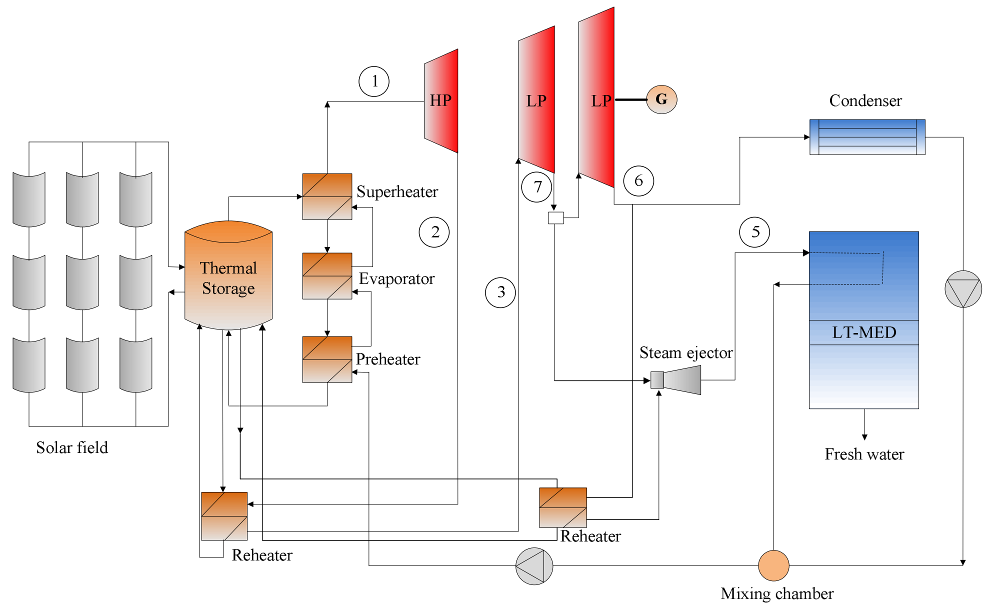

Fig 3. Diagram of the LT-MED-TVC unit integration into a PT-CSP plant, considering extraction from the LP turbine

The third configuration (Fig. 3) is the same concept as the previous one, but in this case one fraction of superheated steam extracted from the LP turbine at 7 is used as live steam in the ejector. Finally, in the fourth case (PT-CSP + RO, Fig. 4), the desalination process is driven by the power output from the CSP plant. The net power of the CSP plant has been considered in all configurations to be 50 MWe, which is the standard current design of many commercial parabolic trough CSP plants [16]. The size of the desalination plants has been determined by the first system proposed (PT-CSP + LT-MED plants) where the exhausted steam coming from the LP turbine is used to drive the desalination plant producing fresh water, as showed in Fig.

1. The production obtained was 46615 m3/day and 24-h operation has been considered.

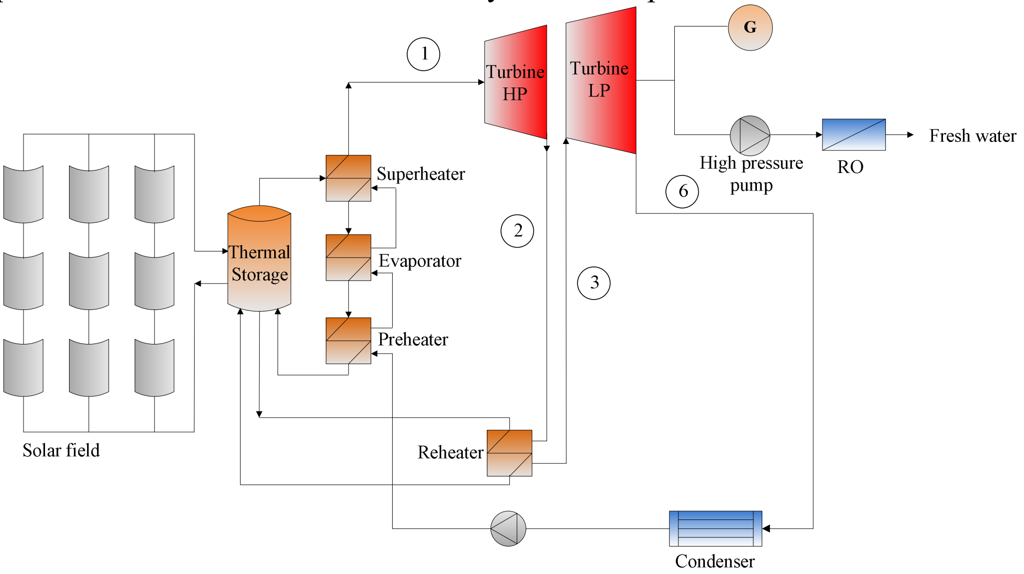

Fig 4. Diagram of the RO unit integration into a PT-CSP plant

Table 1 presents the operating conditions that have been considered in the schemes proposed, which will be used as inputs for the following assessments.

Table 1. Operating conditions at the diagrams in figures 1, 2, 3, 4

Point in the diagram	Magnitude	Value
1	Pressure and temperature	371ºC, 104 bar
2	Pressure	17 bar
3	Pressure and temperature	371ºC, 17 bar
4	Temperature	70ºC
5	Temperature	70ºC
6	Temperature	58ºC
7	Pressure	2, 4, 6, 10, 16 bar

As it can be observed in Table 1, another common condition for all the proposed configurations apart from the first one, is that the steam is allowed to be expanded up to 58ºC (0.18 bar). This value was chosen considering the limitations imposed by the existence of very high ambient temperatures, such as in several Middle East countries, which also are the first potential target to solar water and power cogeneration plants.

With regard to the integrated power and desalination facility, the power block is analyzed considering a steady state model. With the specification of thermodynamic state points, a set of nonlinear, algebraic equations is generated for each cycle. In the current work, the solution was obtained using the Engineering Equation Solver (EES) software [17]. Each case solution yields the cycle unknown state points, along with its net output thermal capacity (thermal power to be provided by the solar field), overall efficiency, thermal power dissipated in the condenser and its gross turbine output. Actual expansion and compression processes in the turbines and pumps, respectively, have been considered. An isentropic efficiency of 85% has been considered for all the turbines and pumps. Actual steam enthalpy at the outlet of the high and low pressure turbines of all the configurations proposed has been calculated through:

$$\eta_{st} = \frac{h_{inlet} - h_{oulet}}{h_{inlet} - h_{outlet,i}} \qquad (1)$$

where η_{st} is the isentropic efficiency, h_{inlet} is the enthalpy of the steam which enters the turbine, h_{outlet} is the actual enthalpy at the outlet of the turbine and $h_{outlet,i}$ is the ideal enthalpy of the steam which leaves the turbine. In the case that some steam is extracted from the turbine (Fig. 3), the enthalpy of the extracted steam has been calculated with the assumption of linear condition line in the h-s diagram between the inlet and the outlet of the turbine:

$$\frac{h_m - h_{outlet}}{h_{inlet} - h_{outlet}} = \frac{s_m - s_{outlet}}{s_{inlet} - s_{outlet}} \tag{2}$$

where h_m and s_m are the enthalpy and the entropy at the point where the steam extraction has been done. In all case studies, the analysis has been carried out considering a net power production of the plant (P_{net}) of 50 MW_e. The net power production of the plant is calculated as the gross turbine output (P_{turb}) minus the power required by the pumps (P_{pumps}) and minus the power required by the desalination plant (P_{desal}):

$$P_{net} = P_{turb} - P_{pumps} - P_{desal} \tag{3}$$

For the calculation of the power required by the desalination plant, a specific electric consumption of 1.5 kWh/m^3 has been considered in the case of the MED plant and 5.5 kWh/m^3 in the case of RO [13]. In both cases 24 h operation and a water production of 46615 m^3/day have been taken into account. The steam flow required by the MED has been calculated by:

$$q_{steam} = \frac{FWF \times \rho}{GOR} \tag{3}$$

where FWF is the fresh water production in m^3/day, ρ is the fresh water density in kg/m^3 (at 35 ºC and 1 bar) and GOR is Gained Output Ratio, which is defined as kilograms of distillate produced for every kilogram of steam supplied to the distillation unit. A GOR of 9.8 has been considered in all cases of MED technology. To calculate the steam ejector flow rates (both live steam and entrained vapor flow rates), a semi-empirical model developed by El-Dessouky [18] has been considered. The model makes use of the field data collected over 35 years by Power [19] for vapor entrainment ratios of steam jet ejectors. The entrainment ratio is the flow rate ratio of the motive steam and the entrained vapor and it can be calculated using:

$$Ra = 0,296\frac{(P_s)^{1,19}}{(P_{ev})^{1,04}}\left(\frac{P_m}{P_{ev}}\right)^{0,015}\left(\frac{PCF}{TCF}\right) \tag{4}$$

where P_m, P_s and P_{ev} are the pressures of the motive steam, compressed vapor and entrained vapor respectively, PCF is the motive steam pressure correction factor and TCF is the entrained vapor temperature correction factor. Following equations were used to calculate PCF and TCF:

$$PCF = 3\times10^{-7}(P_m)^2 - 0,0009(P_m) + 1,6101 \tag{6}$$

$$TCF = 2\times10^{-8}(T_{ev})^2 - 0,0006(T_{ev}) + 1,0047 \tag{7}$$

where P_m is in kPa and T_{ev} is in ºC. Finally, the overall efficiency has been calculated by:

$$\eta_{global} = \frac{P_{net}}{NOTC} \tag{8}$$

where $NOTC$ is the net output thermal capacity, which is given by:

$$NOTC = P_{pcs} + P_{RH} \tag{9}$$

where P_{pcs} and P_{RH} are the power required by the power conversion system and the reheaters of the cycle, respectively. Considering the NOTC of the power block, the solar field size has been determined by a computer model developed in MATLAB. For this purpose, a model is used for the collector based on its thermal losses, its efficiency curve and energy balances [20][21][22]. The model input parameters are: i) North-South orientation; ii) Design point: 12th September (radiation at solar noon = 915.9 W/m^2, ambient temperature = 26.21ºC); iii) Thermal storage capacity for 24-h operation at design day (fossil backup when the solar radiation is not available): iv) The net output thermal capacity of the power block; v) Inlet temperature to the solar field (295°C); vi) Outlet temperature from the solar field (390°C). The simulation was carried out considering a coastal location with 1990 kWh/m^2·yr of DNI radiation, which can also be considered as a good representative for CSP in arid areas close to the sea. Radiation and ambient temperature data have been taken from an available typical meteorological year of a coastal location with similar DNI potential. The PT solar field is based on commercial LS-3 type collector (aperture area of 545 m^2 and a longitude of 99 m). The peak optical efficiency for this type of collectors is 76% and the thermal oil that circulates through the absorber tubes is Monsanto VP-1 (properties determined using Monsanto software).

Results and discussion

Analysis of the power block corresponding to the configuration showed in Fig. 1 was the first to be carried out in order to determine the maximum water production. The results obtained are shown in Fig. 5. As previously indicated, a water production of 46615 m3/day is obtained when all the steam from the turbine outlet (54.72 kg/s) at 70ºC feeds the MED unit, value used as a fixed input parameter for the rest of configurations analyzed within this work in order to always compare the same net production of power and water. Secondly, simulations have been carried out for the diagrams showed in Figs. 2 (PT-CSP + LT-MED-TVC) and Fig. 4 (PT-CSP + RO).

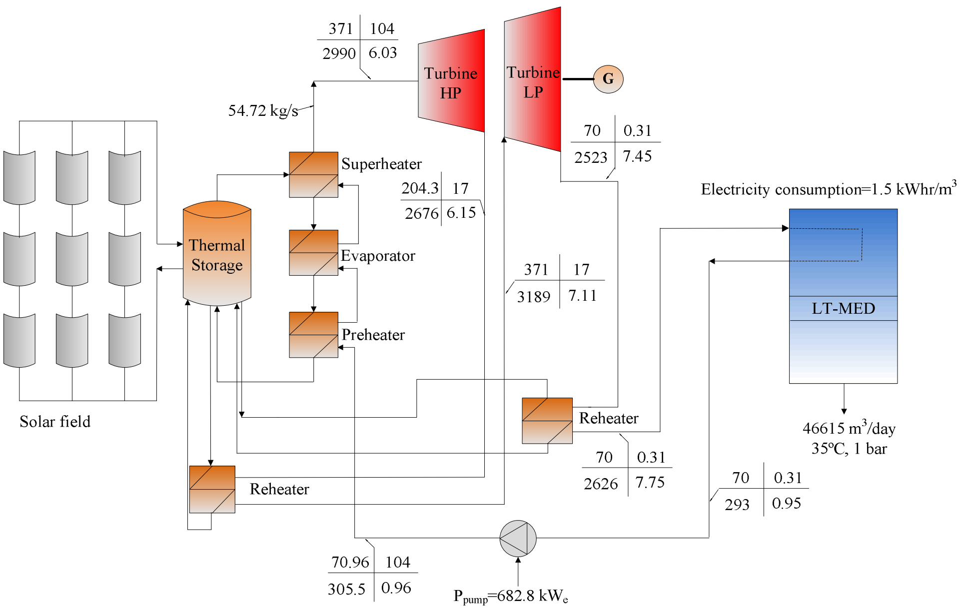

Fig 5: Simulation of LT-MED facility integration into a PT-CSP plant

The results obtained are depicted, respectively, in Figs. 6 and 7. Also, in Fig. 6, more steam than in the previous case (Fig. 5) is generated and used in the HP turbine (69.8 kg/s), but since 26 kg/s are used as live steam in the ejector, only 43.74 kg/s enter the LP turbine. Since 28.66 kg/s out of 43.74 kg/s are used as inlet vapor in the ejector, only 15 kg/s are sent eventually to the condenser. In Fig.7, all the steam from the LP turbine outlet (58.9 kg/s) must be condensed, since no extraction is done in the turbine. Table 2 presents a summary of the Net Output Thermal Capacity (NOTC) to be provided by the thermal storage system to the power + desalination units, the overall efficiency (considering the same net power and including the water production) and the solar field size required, from the simulations of Figures 5 to 7. It also shows the cooling requirement, which is assessed as the percentage of steam flow rate that leaves the LP turbine and cools in the condenser.

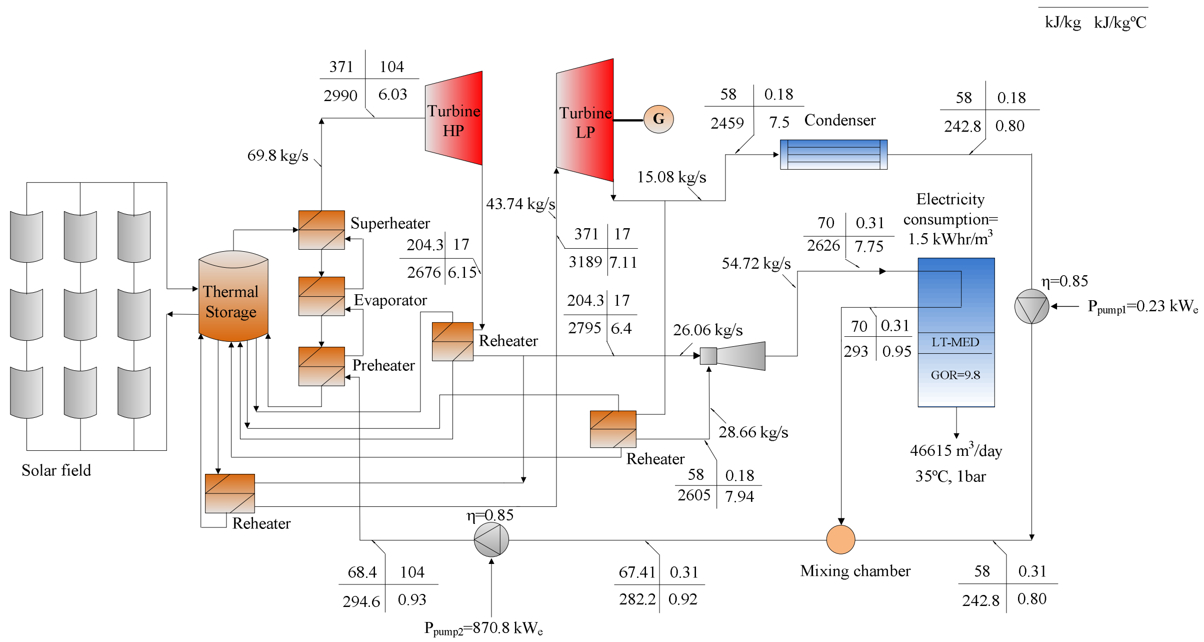

Fig 6: Simulation of an LT-MED-TVC facility integration into a PT-CSP plant

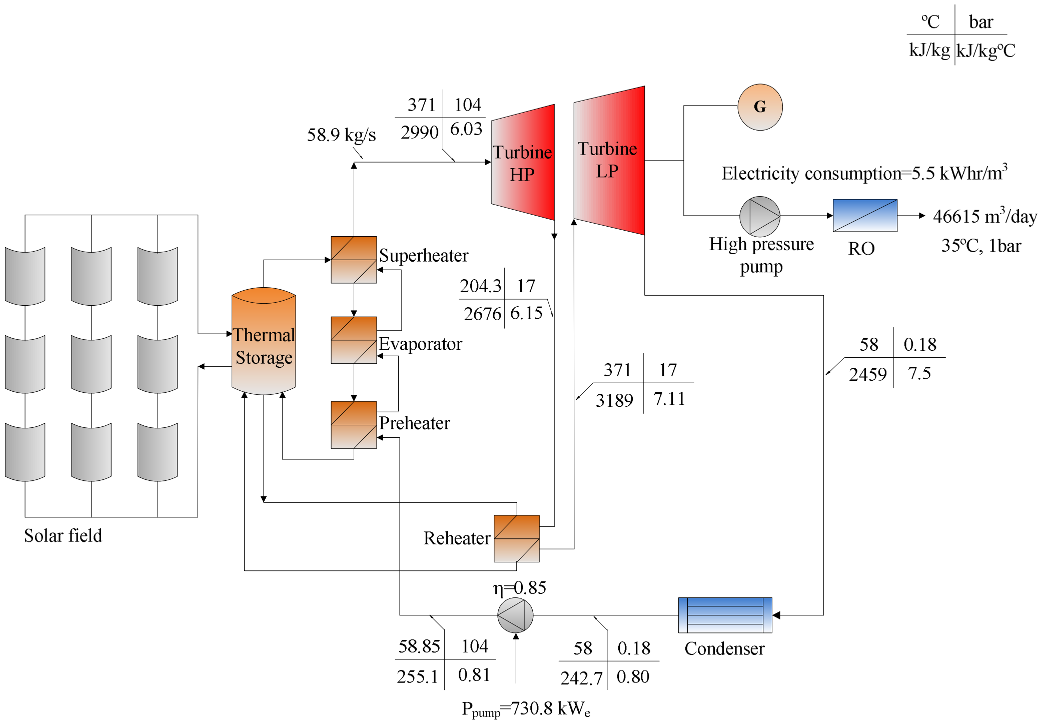

Fig 7: Simulation of RO facility integration into a PT-CSP plant

Table 2. NOTC, overall efficiency, cooling requirements, number of collector per row, number of rows, aperture area resulting from each configuration proposed

Desalination system	NOTC (MW_{th})	Overall Efficiency (%)	Cooling requirement (%)	Collectors per row	Number of rows	Aperture area (m^2)
LT-MED	181	27.7	0	2	722	786,980
RO	191	26.1	100	2	763	831,670

LT-MED-TVC	219	22.9	34.5	2	873	951,570

From Table 2 it can be observed, on one hand, that the integration of the LT-MED plant into the PT-CSP plant needs the lowest NOTC and therefore the smallest solar field. Moreover, unlike in the integration with RO, in this layout no power cooling is required. This result shows that the use of dry cooling in arid locations could make LT-MED more competitive than RO, as opposed to those ones obtained with some case studies using wet cooling [14]. On the other hand, the results show that the integration of a LT-MED-TVC plant into a PT-CSP plant needs the biggest NOTC, since it uses a high exergy steam to feed the steam ejector, resulting also in a decrease of the power block overall efficiency. However, if we compare this configuration with the integration of a RO system, it can be seen that the former requires a lower power plant cooling than the latter. LT-MED-TVC configuration is considered as one interesting option due to its flexibility in the integration with the power production process. One of the reasons is that pressurized steam can be easily transferred from the power block to the desalination unit, in contrast to low pressure ones that needs much bigger piping (due to pressure conditions). In addition to this, LT-MED configuration requires the production rate of the desalination plant to be proportional to the load of the steam turbine and, consequently, the desalination process has to follow the load of the power cycle. In this context, to optimize the integration of a LT-MED-TVC unit into a PT-CSP plant in terms of the heat extraction, several simulations have been carried out taking into account the conditions pointed in Table 1 and the diagram showed in Fig. 3 (point 7). The results obtained, compared to the ones of RO, are represented in Figure 8.

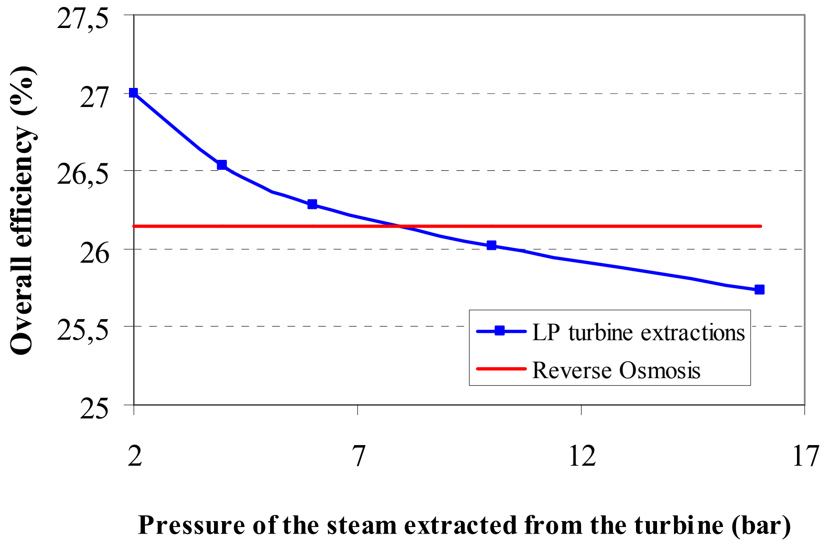

Fig 8: Comparison of the overall efficiency obtained with different LT-MED-TVC configurations (steam extraction at different pressures) against RO unit

As shown in Fig. 8, the higher the pressure of the steam extracted from the turbine is, the lower the overall efficiency of the LT-MED-TVC configuration, being equal to RO efficiency at extracting pressures of about 8 bars.

Economic analysis

To carry out an estimation of the power and water costs of more efficient configurations (PT-CSP/LT-MED and PT-CSP/RO ones), we will use the following definition of Levelized Electricity Cost (LEC):

$$LEC = \frac{crf \times K_{invest} + K_{O\&M} + K_{fuel}}{E_{net}} \tag{10}$$

$$crf = \frac{k_d\left(1+k_d\right)^n}{\left(1+k_d\right)^n - 1} + k_{insurance} \tag{11}$$

With:
- $K_{insurance}$: annual insurance rate (value used = 1%)
- K_{invest}: total investment of the plant
- K_{fuel}: annual fuel cost (not applicable in the case of solar energy without backup)
- k_d: real debt interest rate (value used = 8%)
- n: depreciation period in years (value used = 25 years)
- $K_{O\&M}$: annual operation and maintenance costs
- E_{net}: annual net electricity delivered to the grid

Additional data used to calculate the cost of the solar power are the following:
- From a practical point of view, it is considered a CSP plant with 14 hours of thermal storage (instead of 24), working 24 hours from mid spring to mid autumn and also at nominal turbine capacity the rest of the year.
- Investment cost of the 50 MW PT-CSP plant without thermal storage: 3300 €/$kW_{nominal}$
- Investment cost of thermal storage: 40 €/kWh (stored)
- Solar filed size: 716000 m^2 (about 280 hectares of flat land needed)
- Plant availability: 96%
- Water needed by the power plant to be provided by the desalination plant: 3.3 m^3/MWh_e (nominal capacity of desalination unit must be enlarged to finally deliver a net amount of 46615 m3/day)

The same procedure will be used to the Levelized Water Cost (LWC) estimation. Additional data to calculate the cost of the desalination plant:
- Investment cost of RO facility: 850 €/m^3 day installed (availability: 92%)
- Investment cost of MED facility: 1050 €/m^3 day installed (availability: 98%)
- Specific electricity consumption by RO plant: 5,5 kWh/m^3 (to be provided by the power plant, so the solar field must be enlarged to finally deliver a net amount of 50 MW)
- Specific electricity consumption by MED plant: 1.5 kWh/m^3 (to be provided by the power plant, so the solar field must be enlarged to deliver a net amount of 50 MW)
- Chemical consumption, manpower, membrane replacement, spare parts and all other fixed and variable cost were also considered

The cost results are summarized within the Table 3.

Table 3. Comparative costs of power (50 MW net production) and water (46615 m^3/day net production) cogeneration with PT-CSP/RO and PT-CSP/LT-MED configurations

Desalina-tion system	Thermal storage (hours)	Solar field (m^2)	Adjusted gross power production (MW)	Adjusted gross water production (m3/day)	Invest-ment solar plant (M€)	Investment desal plant (M€)	LEC (€/kWh)	LWC (€/m3)
PT-CSP / RO	14	878547	61.35	51685	399.31	43.93	0.188	0.701
PT-CSP / LT-MED	14	854467	59.67	51244	391.49	53.81	0.185	0.762

Conclusions

Two types of LT-MED plants have been considered: a low temperature multi-effect distillation (LT-MED) plant, using the exhausted steam from the CSP plant as the source of the heat, and a novel system consisting of low temperature multi-effect distillation plant powered by the steam produced from a thermal vapor compressor (TVC). In this case, unlike in the typical thermal vapor compression MED process (TVC-MED), the entrained vapor to be used in the steam ejector comes from the exhausted steam of the CSP plant instead of an intermediate effect of the desalination plant. This new concept has a strong potential since is useful for the coupling of any thermal desalination process to a CSP plant. Within this concept (LT-MED-TVC), different schemes have been studied: a system that uses the high exergy steam at the high pressure turbine outlet as motive steam in the TVC, and others that use steam extracted at different pressures from the low pressure turbine as the motive steam in the ejector. Some main results are following: the integration of a LT-MED plant into a PT-CSP plant is the most efficient thermodynamically of all configurations proposed, besides no power cooling is required and therefore any condenser would be necessary. Although power production is reduced due to the higher pressure of the steam at the outlet of the turbine, the reduction is smaller than in other regions where the cold-end temperature is lower. The integration of a LT-MED-TVC into a PT-CSP plant resulted in the smallest overall efficiency. However, when steam extractions from the low pressure turbine are carried out the system is more efficient and the cooling requirements are lower compared to CSP+RO system. In addition to this, as opposed to the system CSP+LT-MED, this one does not depend on the load of the steam turbine, what can make it more convenient in some cases. When costs are analyzed, comparing the two more efficient configurations (PT-CSP/RO and PT-CSP/LT-MED), considering 58ºC/0.18 bar of exhaust turbine steam conditions and 5.5 kWh/m^3 of Reverse Osmosis power requirements, the results of final power + water costs, are very similar.

Used nomenclature and acronyms

CSP:	Concentrating Solar Power
CSP+D:	Concentrating Solar Power and Desalination
EES:	Engineering Equation Solver
FWF:	Fresh water production
GOR:	Gained Output Ratio
LEC:	Levelized Electricity Cost
LWC:	Levelized Water Cost
LT-MED:	Low-Temperature Multi-Effect Distillation
LT-MED-TVC:	Low-Temperature Multi-Effect Distillation with Thermal Vapor Compression
MED:	Multi-Effect Distillation
MENA:	Middle East and North African countries
NOTC:	Net output thermal capacity to be provided by the thermal storage system
PCF:	Motive steam pressure correction factor
PT:	Parabolic Trough
PT-CSP:	Concentrating Solar Power plant based on Parabolic Trough collectors
RO:	Reverse Osmosis
TCF:	Entrained vapor temperature correction factor
TVC:	Thermal Vapor Compression
TVC-MED:	Thermal Vapor Compression with Multi-Effect Distillation

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